AN INTERPRETATION OF THE EVIDENCE FOR TEV EMISSION FROM GAMMA-RAY BURST 970417A

Tomonori Totani
Theory Division, National Astronomical Observatory
Mitaka, Tokyo 181-8588, Japan
e-mail: totani@th.nao.ac.jp

To Appear in the Astrophysical Journal Letters

ABSTRACT

The Milagrito collaboration recently reported evidence for emission of very high energy gamma-rays in the TeV range from one of the BATSE GRBs, GRB 970417a. Here I discuss possible interpretations of this result. Taking into account the intergalactic absorption of TeV gamma-rays by the cosmic infrared background, I found that the detection rate (one per 54 GRBs observed by the Milagrito) and energy fluence can be consistently explained with the redshift of this GRB at $z \sim 0.7$ and the isotropic total energy in the TeV range, $E_{\rm TeV,iso} \gtrsim 10^{54}$ erg. This energy scale is not unreasonably large, but interestingly similar to the maximum total GRB energy observed to date, in the sub-MeV range for GRB 990123. On the other hand, the energy emitted in the ordinary sub-MeV range becomes $E_{\rm MeV,iso} \sim 10^{51}$ erg for the GRB 970417a, which is much smaller than the total energy in the TeV range by a factor of about 10^3. I show that the proton-synchrotron model of GRBs provides a possible explanation for these observational results. I also discuss some observational signatures expected in the future experiments from this model.

Subject headings: acceleration of particles — cosmic rays — diffuse radiation — galaxies: evolution — gamma-rays: bursts — gamma-rays: theory

1. INTRODUCTION

Gamma-ray bursts (GRBs) have been the most mysterious astronomical phenomenon in the universe for about 30 years after the discovery (Klebesadel, Strong, & Olson 1973). One of the reasons why the GRB phenomenon is difficult to understand is that GRBs had been observed only in the soft gamma-ray band for a long time. Detection of GRBs in other wavelengths is quite valuable for the progress of the GRB study, as proved by the dramatic progress in recent years following the discovery of afterglows in longer wavelengths of X, optical and radio bands (see, e.g., Piran 1999 for a recent review). Detection of gamma-rays harder than the ordinary sub-MeV band is also important information for better understanding of GRBs. It has been confirmed that emission from GRBs extends up to ~ 10 GeV, as seen in the famous long-duration GeV emission from GRB 940217 (Hurley et al. 1994). There have been some suggestive results for the emission beyond TeV range (Amenomori et al. 1996; Padilla et al. 1998), although these results were not claimed as firm detections of GRBs.

Recently the Milagro group reported evidence for TeV emission from one (GRB 970417a) of the 54 BATSE GRBs in the field of view of their detector, Milagrito (proto-type of Milagro) (Atkins et al. 2000). An excess of gamma-rays above background is clearly seen during the duration of this burst in the BATSE error circle, and the chance probability of such an event after examining 54 GRBs is estimated as 1.5×10^{-3}, giving stronger evidence for TeV emission compared with the earlier observations in this energy band. If this signal is truly from the GRB, the TeV fluence must be at least 10 times greater than the sub-MeV fluence of this GRB without taking into account the intergalactic absorption of TeV gamma-rays. The impact on the GRB energetics would be quite strong.

In this letter I discuss theoretical implications of this interesting event, assuming that the signal observed by the Milagrito is truly from the GRB 970417a. I first try to estimate a likely value of the redshift and energetics of this GRB from the observed energy fluence and detection rate (1 per 54 GRBs), under the assumption that this GRB is not a peculiar GRB. I then discuss whether this extreme phenomenon can be explained in a reasonable theoretical framework. I show that the proton-synchrotron model of

GRBs (Totani 1998b, 1999) gives a possible explanation for the Milagrito result.

Throughout this letter I use the isotropic energy for the total energy of GRBs. My analysis does not depend on the unknown collimation factor of GRBs, and the actual energy emitted by the central engine can be much smaller than the isotropic energy if GRBs are strongly collimated, jet-like explosions.

2. REDSHIFT AND ENERGETICS OF GRB 970417A

The basic assumption is that GRB 970417a is the nearest GRB to us among the 54 GRBs observed by the Milagrito. The unknown luminosity function of GRBs in the TeV range makes this assumption less reliable, but this is reasonable because detectability of TeV gamma-rays from cosmological GRBs very rapidly decreases with increasing redshift, due to the well-known effect of intergalactic absorption by the cosmic infrared background radiation (see, e.g., Salamon & Stecker 1998; Primack et al. 1999). Another argument supporting this assumption will be given in §4.

We can estimate the fraction of GRBs within a given redshift z of all GRBs detectable by the BATSE satellite, $N(<z)$, if we know the sub-MeV luminosity function of GRBs, GRB rate history as a function of z, and the threshold flux of the BATSE. Let L_p be the peak photon-number luminosity (i.e., not energy) in the restframe 50–300 keV range, and P be the observed peak photon flux in the BATSE range of 50–300 keV. These two are related as:

$$P(L_p, z) = \frac{(1+z)^{2-\alpha}}{4\pi d_L^2} L_p \ , \tag{1}$$

where d_L is the standard luminosity distance and I have assumed a power-law spectrum of GRBs in the sub-MeV range with a spectral index α, as $dL_p/d\varepsilon \propto \varepsilon^{-\alpha}$. The observed rate of GRBs with a given set of (L_p, z) is given as

$$\frac{d^2N}{dL_p dz} = \phi(L_P) \frac{R_{\rm GRB}(z)}{(1+z)} \frac{dV}{dz} \ , \tag{2}$$

where $\phi(L_p)$ is the luminosity function of GRBs, $R_{\rm GRB}$ is the comoving rate density of GRBs as a function of redshift, and dV/dz is the comoving volume element of the universe. The factor $(1+z)^{-1}$ comes from the cosmological time dilation effect. I assume that the GRB rate evolution traces the star formation history in the universe (Totani 1997). The form of the star formation rate evolution is modeled based on the data compiled by Madau, Pozzetti, & Dickinson (1998). Then $N(<z)$ is given as

$$N(<z) = \frac{\int_0^z dz \int dL_p (d^2N/dL_p dz) \Theta[P(L_p,z) - P_{\rm th}]}{\int_0^\infty dz \int dL_p (d^2N/dL_p dz) \Theta[P(L_p,z) - P_{\rm th}]} \ , \tag{3}$$

where Θ is the step function [i.e., $\Theta(x) = 1$ and 0 for $x > 0$ and $x < 0$, respectively], and $P_{\rm th}$ is the detection threshold of the BATSE ($P_{\rm th} \sim 0.3$ photons cm^{-2}sec^{-1}, Meegan et al. 1996). In this letter I assume a form of the luminosity function of GRBs as logarithmically flat [$\phi(L_p) \propto L_p^{-1}$] within a range of $(L_{p,\rm min}, L_{p,\rm max}) = (10^{57}, 10^{59})$ [photons s^{-1}], based on the observed luminosity distribution of GRBs with secure redshifts (see, e.g., Table 1 of Lamb & Reichart 2000). The spectral index α is set to 1, which is a rough average of GRB spectra (Mallozzi, Pendleton, & Paciesas 1996). I use a reasonable set of cosmological parameters of $H_0 = 70$ km/s/Mpc and $(\Omega_0, \Omega_\Lambda) = (0.3, 0.7)$.

In Fig. 1, I show $N(<z)$ as a function of redshift by the dot-dashed line. [See the right-hand-axis for the scale of $N(<z)$]. It becomes consistent with the detection rate of GRBs by the Milagrito detector, 1/54, at redshift ~ 0.7. (The vertical solid line shows the redshift corresponding to the detection rate of 1/54, and the shaded region shows a redshift range in which the detection rate is consistent within a factor of two.) Also shown by the dashed line is the total isotropic energy emitted in the BATSE range, $E_{\rm MeV}$, which is estimated by the BATSE fluence of the GRB 970417a, 3.9×10^{-7} erg cm^{-2}, in all the four energy channels of the BATSE ($>$ 20 keV). [The latest BATSE catalog at MSFC is available at http://cossc.gsfc.nasa.gov/cossc/BATSE.html]. The isotropic energy in the sub-MeV band then becomes $\lesssim 10^{51}$ erg in the likely redshift range. The observed total sub-MeV energy of the GRBs with secure redshifts is widely distributed in a range $\sim 10^{51}$–10^{54} erg, and GRB 970417a belongs to a class of the least energetic GRBs in the sub-MeV band.

In order to estimate the total energy emitted in the TeV range, the absorption optical depth of TeV gamma-rays due to the cosmic infrared background is necessary. I have calculated this optical depth as a function of the source redshift and observed photon energy, by using a model of luminosity density evolution of stellar lights in the universe (Totani, Yoshii, & Sato 1997). The standard formulation for the calculation of optical depth from the luminosity density evolution in the universe is given in e.g., Salamon & Stecker (1998). The dust-emission component is calculated assuming that the dust emission spectrum is the same as that in the solar neighborhood and the fraction of stellar light absorbed by dust is determined to reproduce the far infrared background radiation measured by the COBE satellite (Hauser et al. 1998). I have checked that this model of optical depth is quantitatively consistent with earlier publications within the model uncertainties (e.g., Salamon & Stecker 1998; Primack et al. 1999).

Fig. 2 shows the observed photon energy (ε) corresponding to several values of optical depth [$\tau(z, \varepsilon)$] as a function of the source redshift.

The events observed by the Milagrito are considered to be gamma-rays above 50 GeV (Atkins et al. 2000), and an estimate of the TeV fluence of the GRB 970417a is given as a function of the upper cut-off energy and spectral index (see Fig. 4 of Atkins et al. 2000). Here I assume the spectral index of 1.5, which is the standard photon index of synchrotron radiation with particle index of 2. If the TeV spectrum is harder or softer than this, the estimate of the total energy in TeV range becomes smaller or larger, respectively (see Fig. 4 of Atkins et al. 2000). I use the photon energy corresponding to the intergalactic optical depth τ=1, denoted as $\varepsilon_{\tau=1}(z)$, as the upper cut-off energy, unless this energy is smaller than 50 GeV. Then we can estimate the total isotropic energy emitted in the TeV range as

$$E_{\rm TeV} = \frac{4\pi d_L^2}{(1+z)} F_{\rm TeV}(\varepsilon_{\rm cut}) \exp[\tau(z, \varepsilon_{\rm cut})] \ , \qquad (4)$$

where the upper cut-off energy is $\varepsilon_{\rm cut} = \max(50 \text{ GeV}, \varepsilon_{\tau=1})$, and $F_{\rm TeV}$ is the observed TeV fluence which is a function of the upper cut-off energy. The result is shown by the solid line in Fig. 1 as a function of redshift.

From these results, a possible interpretation is that GRB 970417a was located at $z \sim 0.7$ emitting isotropic energies of $\gtrsim 10^{54}$ and $\lesssim 10^{51}$ erg in the TeV and sub-MeV range, respectively. It is interesting to note that the energy emitted in the TeV range is similar to that in the sub-MeV range of the most energetic GRB observed to date: GRB 990123, whose total isotropic energy was estimated as $\sim 3 \times 10^{54}$ erg (Kulkarni et al. 1999). Therefore the extremely large isotropic energy in the TeV range for GRB 970417a is not too large for the total energy budget of GRBs. In fact, we do not know why most of the energy of GRBs is emitted in the sub-MeV range, and there is no robust theoretical argument which excludes a possibility that most of the total GRB energy is emitted in other photon energy bands. In fact, such an extreme phenomenon has been predicted by the proton-synchrotron model of GRBs (Totani 1998b; 1999). In the rest of this letter I discuss whether this model can explain the Milagrito result.

3. INTERPRETATION BY THE PROTON-SYNCHROTRON MODEL

Full description of this model has already been given in Totani (1998b; 1999), and here I summarize the qualitative feature of the model.

Currently the most popular explanation for the GRB phenomenon is dissipation of the kinetic energy of ultra-relativistic bulk motion with a Lorentz factor of $\Gamma \gtrsim 10^{2-3}$, in internal shocks which are generated by relative velocity differences of relativistic shells ejected from the central engine. All the total energy ejected as relativistic bulk motion cannot be dissipated in internal shocks, and hence the total energy truly emitted as kinetic motion ($E_{\rm iso}$) should be larger than the observed total energy of gamma-rays, $E_{\gamma,{\rm iso}}$, at least by a factor of several. Therefore, the most energetic class of GRBs, such as GRB 990123, must emit quite a large amount of energy, $E_{\rm iso} \gtrsim 10^{55}$ erg. If the efficiency of the internal shock is not so high, we may have to consider an isotropic energy reaching $\sim 10^{56}$ erg. Therefore, if GRBs are produced by stellar death events, GRBs must be strongly collimated at least by a factor of $(4\pi/\Delta\Omega) \sim 100$ to reduce the actual energy emitted from the central engine.

Since the origin of the GRB energy is relativistic bulk motion, protons should carry a much larger amount of energy than electrons by a factor of $m_p/m_e \sim 2{,}000$ in the initial stage of the internal shock generation. It is very uncertain what fraction of the proton energy is converted into electrons, but the simplest Coulomb interaction cannot transfer the proton energy into electrons within the typical time scale of GRBs (Totani 1998a, 1999). The soft gamma-rays are generally considered to be generated by electrons, because of the short time variability of GRBs. Therefore it is not unreasonable that, in some GRBs, only $(m_e/m_p) \sim 10^{-3}$ of the total kinetic energy is carried by electrons and then emitted as soft gamma-rays. If the hidden energy carried by protons is directly emitted in the TeV range, then much more energy can be radiated in the TeV range than in the sub-MeV range by a factor of almost one thousand.

GRBs are known as a possible site for the acceleration of protons up to 10^{20} eV, which are observed on the Earth as ultra-high energy cosmic rays (Waxman 1995; Vietri 1995; Milgrom & Usov 1995). I have already shown (Totani 1998b) that, when $E_{\rm iso} \gtrsim 10^{55}$ erg and the magnetic field is as strong as the energy density of the shocked region, synchrotron radiation of protons accelerated to 10^{20} eV can be an efficient emission process because the cooling time of such protons is comparable with the typical GRB duration ($\sim$ 10 sec) in the observer's frame. The energy of these synchrotron photons for an observer is about 1–10 TeV, and strong TeV emission from GRBs is possible. I suggest that the TeV gamma-rays possibly detected by the Milagrito were produced by this mechanism.

On the other hand, it may also be possible that a physical process works as an energy conveyor from the hidden energy reservoir (i.e., protons) into electrons (or positrons). If the energy transfer is almost complete in a GRB, a significant fraction of $E_{\rm iso}$ can be radiated as gamma-rays in the sub-MeV range. I have pointed out (Totani 1999) that $e^{\pm}$-pair creation by TeV photons of proton-synchrotron might work as the new energy channel for the energy transfer from protons into electrons and positrons, giving an explanation for the energetic sub-MeV GRB phenomenon such as GRB 990123. Proton-synchrotron photons interact with low energy electron-synchrotron photons and create $e^{\pm}$ pairs. It can also be shown that the photon energy range of the synchrotron radiation of the created pairs becomes about MeV, i.e., consistent with the BATSE range.

Then what is the crucial parameter which determines whether a GRB is bright in TeV or MeV? The GRB luminosity in the sub-MeV range is determined by the efficiency of energy transfer from protons into $e^{\pm}$ pairs, i.e., the opacity of pair-production reaction for the proton-synchrotron TeV photons. Based on the typical fireball parameters of GRBs, this pair-production opacity is typically of order unity, and strongly depends on the bulk Lorentz factor of GRBs by the special relativistic effect as $\tau \propto \Gamma^{-5}$ in a simple internal shock model (Totani 1999; see also Baring & Harding 1997; Böttecher & Dermer 1998). Because of this strong dependence of the pair-creation optical depth on Γ, a modest dispersion in Γ by a factor of 3–4 from one GRB to another results in drastic change in the sub-MeV energetics of GRBs by a factor of up to $\sim 10^3$ (Totani 1999). A large value of Γ results in negligible optical depth to pair-creation and hence a GRB strong in TeV such as GRB 970417a, while a small Γ in the inverse case of a GRB strong in MeV such as GRB 990123.

This mechanism gives a natural explanation for the wide dispersion in the observed total GRB energy in the sub-MeV range, with almost no correlation with the afterglow luminosity (Totani 1999). This model assumes a relatively uniform distribution of the total kinetic energy emitted from the central engine, and sub-MeV luminosity of GRBs is not correlated with the kinetic energy injected into interstellar/circumstellar medium. It may be similar to a see-saw between sub-MeV and TeV energies, in which the total kinetic energy of GRBs is roughly the same for all GRBs and difference of GRB energetics is whether dominant emission is in TeV or MeV bands.

To summarize, GRB 970417a observed by the Milagrito can be understood as a GRB with the isotropic kinetic energy $E_{\rm iso} \gtrsim 10^{55}$ erg ejected from the central engine, a significant fraction of which is radiated in the TeV range by the synchrotron radiation of ultra-high-energy protons, with almost no energy transfer from protons into electrons due to a relatively large value of Γ.

4. DISCUSSION

Here I discuss some observational signatures expected in future experiments from the interpretation presented in this letter.

The proton-synchrotron model predicts that the ratio of TeV/MeV luminosities drastically changes from burst to burst by the difference of energy transfer efficiency from protons into electrons and positrons. When the optical depth to the pair-creation reaction is much larger than unity, it is possible that the TeV energy fluence is much weaker than the sub-MeV fluence in contrast to the GRB 970417a, even after the intergalactic absorption of TeV gamma-rays is corrected. However, a generic prediction of this model is that the total of isotropic TeV and sub-MeV energies is about $\sim 10^{54-55}$ erg for all GRBs with much smaller scatter than that of the sub-MeV or TeV isotropic energies.

The assumption that the GRB 970417a is the closest burst to us may be wrong if TeV luminosity of GRBs drastically changes from burst to burst, as expected in the proton-synchrotron model. However, I emphasize that this assumption is, in this case, conservative from a theoretical point of view. The argument that the redshift of the closest GRB in the 54 BATSE GRBs is about $z \sim 0.7$ is based only on the sub-MeV luminosity function of GRBs and GRB rate evolution. Then, if the GRB 970417a is not the closest but intrinsically even brighter GRB in TeV, its distance must be larger than $z \sim 0.7$. Therefore this estimate can be considered as a lower limit of the redshift. If the redshift is significantly larger than 0.7, the TeV isotropic energy of this burst would be much larger than $\sim 10^{54}$ erg, which would be quite difficult to explain by the stellar death models even if we invoke a strongly collimated jet-like explosion. Hence I consider the estimate of redshift and energetics presented here is reasonable.

The Milagro detector, which has significantly increased the sensitivity to GRBs between 0.1 and 10 TeV, is now operating to search for GRBs (Atkins et al. 2000). If the signal observed by the Milagrito is truly from GRB 970417a, the Milagro detector would detect an event similar to GRB 970417a with better signal-to-noise ratio. It is also important to detect GRBs more distant than GRB 970417a to increase the detection rate, because $N(< z)$ rapidly increases with redshift. It is unfortunate that the intergalactic optical depth of TeV gamma-rays also rapidly increases, and hence improvement of detector sensitivity does not significantly extend the distance of marginally detectable GRBs. The cut-off photon energy by the intergalactic absorption falls below ~ 50 GeV at $z \sim 1.2$, where $N(> z) \sim 0.1$. Therefore it seems unlikely that the detection rate in the TeV range is increased to more than 1 per 10 BATSE-detected GRBs, even if the detector sensitivity is significantly improved.

Another improvement of the Milagro over Milagrito is the improved of spectral information. If we can measure the spectral cut-off by the intergalactic absorption for GRBs with known redshifts, it would provide information on the flux of the cosmic infrared background radiation as well as its evolution to $z \gtrsim 0.5$, which would be valuable for the study of galaxy formation and evolution.

REFERENCES

Amenomori, M. et al. 1996, A&A 311, 919
Atkins, R. et al. 2000, to appear in ApJ Letters (astro-ph/0001111)
Baring, M.G. & Harding, A.K. 1997, ApJ, 491, 663
Böttcher, M. & Dermer, C.D. 1998, ApJ, 499, L131
Hauser, M.G. et al. 1998, ApJ, 508, 25
Hurley, K. et al. 1994, Nature, 372, 652
Klebesadel, R.W., Strong, I.B., & Olson, R.A. 1973, ApJ, 182, L85
Kulkarni, S.R. et al. 1999, Nature, 393, 35
Lamb, D.Q. & Reichart, D.E. 2000, to appear in ApJ, astro-ph/9909002
Madau, P., Pozzetti, L., & Dickinson, M. 1998, ApJ, 498, 106
Mallozzi, R. S., Pendleton, G. N., & Paciesas, W. S. 1996, ApJ, 471, 636
Meegan, C.A. et al. 1996, ApJS, 106, 65
Milgrom, M. & Usov, V.V. 1995, ApJ, 449, L37
Padilla, L. et al. 1998, A&A, 337, 43
Piran, T. 1999, Phys. Rep. 314, 575
Primack, J.R., Bullock, J.S., Somerville, R.S., & MacMinn, D. 1999, Astropart. Phys., 11, 93
Salamon, M.H & Stecker, F.W. 1998, ApJ, 493, 547
Totani, T., Yoshii, Y., & Sato, K. 1997, ApJ, 483, L75
Totani, T. 1997, ApJ, 486, L71
Totani, T. 1998a, ApJ, 502, L13
Totani, T. 1998b, ApJ, 509, L81
Totani, T. 1999, MNRAS, 307, L41
Vietri, M. 1995, ApJ, 453, 883
Waxman, E. 1995, Phys. Rev. Lett. 75, 386

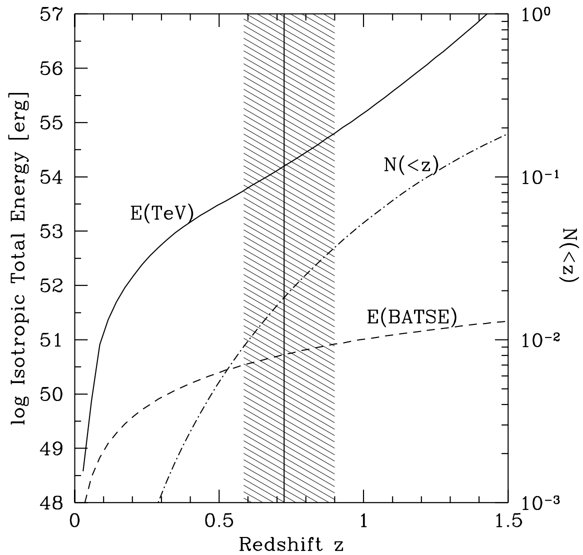

FIG. 1.— The dot-dashed line shows the fraction of GRBs within a given redshift of all the BATSE GRBs, $N(< z)$, assuming logarithmically flat luminosity function of GRBs and GRB rate evolution proportional to the star formation rate in the universe (see text). See the right-hand-side scale for $N(< z)$. The shaded region shows a redshift range which is consistent with the detection rate of GRBs in the TeV range by the Milagrito, 1 per 54 BATSE GRBs, within a factor of two. The vertical solid line in the center of the shaded region indicates the redshift exactly consistent with the detection rate of 1/54. The solid and dashed lines are the estimates of total isotropic energy emitted from GRB 970417a in the TeV and BATSE ranges, respectively. The intergalactic absorption of TeV gamma-rays is taken into account for the total TeV energy.

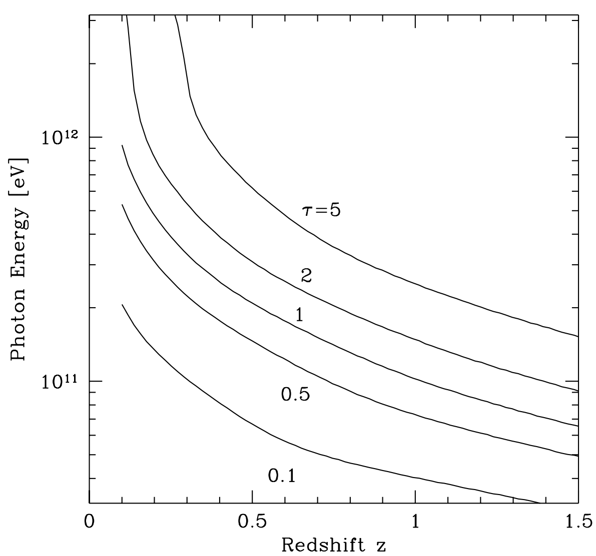

FIG. 2.— Contour map of the intergalactic optical depth of very high energy gamma-rays, as a function of observed photon energy and source redshift. The value of optical depth, τ, is indicated in the figure.